Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **25**, 421–436 (2000)

CHARACTER OF CHANNEL PLANFORM CHANGE AND MEANDER DEVELOPMENT: LUANGWA RIVER, ZAMBIA

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Received 16 September 1998; Revised 7 June 1999; Accepted 25 August 1999

ABSTRACT

Air photo interpretation and field survey were used to examine rates and patterns of planform change over the last 40 years on an 80 km reach of the Luangwa River, Zambia. The river, a tributary of the Zambezi, is a 100–200 m wide, medium sinuosity sand-bed river (sinuosity index 1·84). High rates of channel migration (<33 m a^{-1}) and cutoffs on meandering sections are frequent. Some meandering reaches, however, have remained relatively stable. A form of anastomosing with anabranches up to 14 km in length is also a characteristic. Patterns of meander development vary between bends but all can be described in relation to traditional geomorphic models; change occurs by translation, rotation, double-heading, concave bank bench formation and cutoff causing river realignment. At the local scale spatial variability in bank resistance, induced by floodplain sedimentology, controls rate of bank erosion, and valley-side channel 'deflection' is also apparent.

KEY WORDS: planform; channel change; avulsion; concave bank bench

INTRODUCTION

In comparison with temperate environments there is a limited number of in-depth studies examining the nature of river planform change on tropical rivers. Notable studies include those of Rutherford and Bishop (1996) on the Mekong River, Speight (1965b) on the Auranga River and Salo *et al.* (1986) on the Amazon and Ucayili. More generally channel morphological studies on tropical rivers are rare. Studies of tropical river geomorphology include the work of Pickup and Warner (1984) and Blake and Ollier (1971) on the Fly and Purari rivers in Papau New Guinea, Gupta and Dutt (1989) and Speight (1965a) on the Auranga River in India, and Savat (1975) on the Zaire River. As a result of this restricted interest in tropical river geomorphology, Gupta (1995) has stated the need for more research into channel form in the seasonal tropics. Indeed Gupta and Dutt (1989) suggest that humid tropical rivers with both a strong seasonality in discharge and a large sand sediment load may not fit well with existing geomorphic or sedimentological models.

The geomorphic and engineering interest in river planform change stems largely from the fact that rivers migrate, eroding and depositing as they go. As a result, engineering structures are often threatened and there is thus the need for predictive capability with respect to river planform change on highly mobile rivers. A knowledge of rates and patterns of planform change is also important in understanding habitat diversity in floodplain environments. Within temperate regions many studies have focused on planform changes in meandering rivers; a useful review is provided by Hooke (1996). However, even for temperate rivers, the ability to predict future change is limited despite repeated attempts and advances in the modelling of meander flow hydraulics.

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Contract/grant sponsor: British Council
Contract/grant sponsor: EDF/Zambian National Parks and Wildlife Service
Contract/grant sponsor: University of Zambia.

This paper examines the nature of channel planform change, the extent to which changes observed validate existing models of meander development, and the role of spatial variation in bank resistance in controlling meander development on the Luangwa River, Zambia. The findings may be valid for similar tropical rivers but more widespread research is required to produce a generally applicable model. The findings of this paper were the basis for applying a kinematic wave model to model planform change as suggested by Ferguson (1989). The kinematic wave model in this case is operated within an Arc/Info GIS framework. Channel change, in the study area, is highly significant to humans in that within the South Luangwa National Park a number of safari lodges are sited on the outside of meander bends and are threatened by bank erosion. Lodge location on the outside of meanders with steep eroding banks affords protection from predators such as crocodiles and allows viewing of animals which use the sandy point bars for access to the river edge to drink. Because of the loss of lodges to bank erosion or the setting up of new lodges, there is an interest in the identification of stable reaches and/or rates and direction of channel movement.

BACKGROUND

Meander bend migration has been explained at its most simple by water being directed towards the outer bank by centrifugal forces and superelevation of water levels. This results in the potential for erosion on the outer bank and the transportation of eroded sediment towards the inner bank. According to this theory maximum bank erosion rates will be at and just downstream of the apex (near the inflection point) leading to down-valley translation of meander bends. Hooke (1980) identified four simple models of meander bend development: meander translation, rotation, extension, and a combination of these three. The possibility of a relationship between migration rate and channel curvature has also been advanced. Bagnold (1960) argued that total resistance to flow around a bend depends upon the ratio of radius of curvature (r) to channel width (w), with a local minimum ratio at approximately 2. On tighter bends flow separation induces greater resistance. Empirical evidence for this theory was found on the Beatton River, British Columbia, by Hickin and Nanson (1975, 1984). Air photo mapping and dendrochronology on forested scroll bars allowed the authors to reconstruct the pattern and chronology of bend migration. Migration rates were greatest where the critical curvature was between 2 and 3 and fell rapidly beyond this critical range of values. This phenomenon is now well accepted (Hooke, 1996). The path of maximum migration was commonly found to change as a bend develops leading to uneven geometric evolution and lobe development, or what have elsewhere been described as double-headed bends (Hooke, 1996); associated with double-heading is the creation of a riffle at the bend apex.

Flow separation on high sinuosity bends has also been used to explain the formation and development of deposition forms known as concave bank benches (Hickin, 1979; Nanson and Page, 1983) on the outer bank of meander bends, altering bend migration patterns away from the classic text book forms. Concave bank benches have been observed on tight bends on the Missippippi River (Carey, 1969), rivers in New South Wales (Nanson and Page, 1983; Woodyer, 1975), Canada (Hickin, 1979) and Wales (Lewin, 1978). Skewed meander forms have also been noted as being typical of meandering rivers by Parker *et al.* (1989), and Lapointe and Carson (1986). Ferguson (1989), using a lagged kinematic wave model, was also able to simulate meander development in which asymmetric and multi-lobed meanders of realistic appearance developed. Asymmetry, in the model, depended on a spatial lag in the relationship between bend curvature and erosion rate and secondary lobes develop when migration is locally restricted by excessive curvature. Within a heterogeneous floodplain, sedimentological differences in the resistance of bank sediments to erosion are also going to distort meander shapes. Ikeda (1989) thus found channel planform and migration rates to be strongly influenced by the presence and distribution of cohesive bank sediments. Similarly Hooke (1980) noted the importance of the silt and clay fraction in bank resistance. Friedkin (1945) for instance, working on the Mississippi River, noted the importance of the high silt/clay fraction within old channels in resisting erosion. Meander directions are also likely to be 'deflected' where freely meandering bends meet valley sides. Moreover, rates of migration will vary along a river in the presence of an increase or decrease in stream power. Hooke (1980) obtained a regression equation between migration rate of meander loops and upstream drainage area.

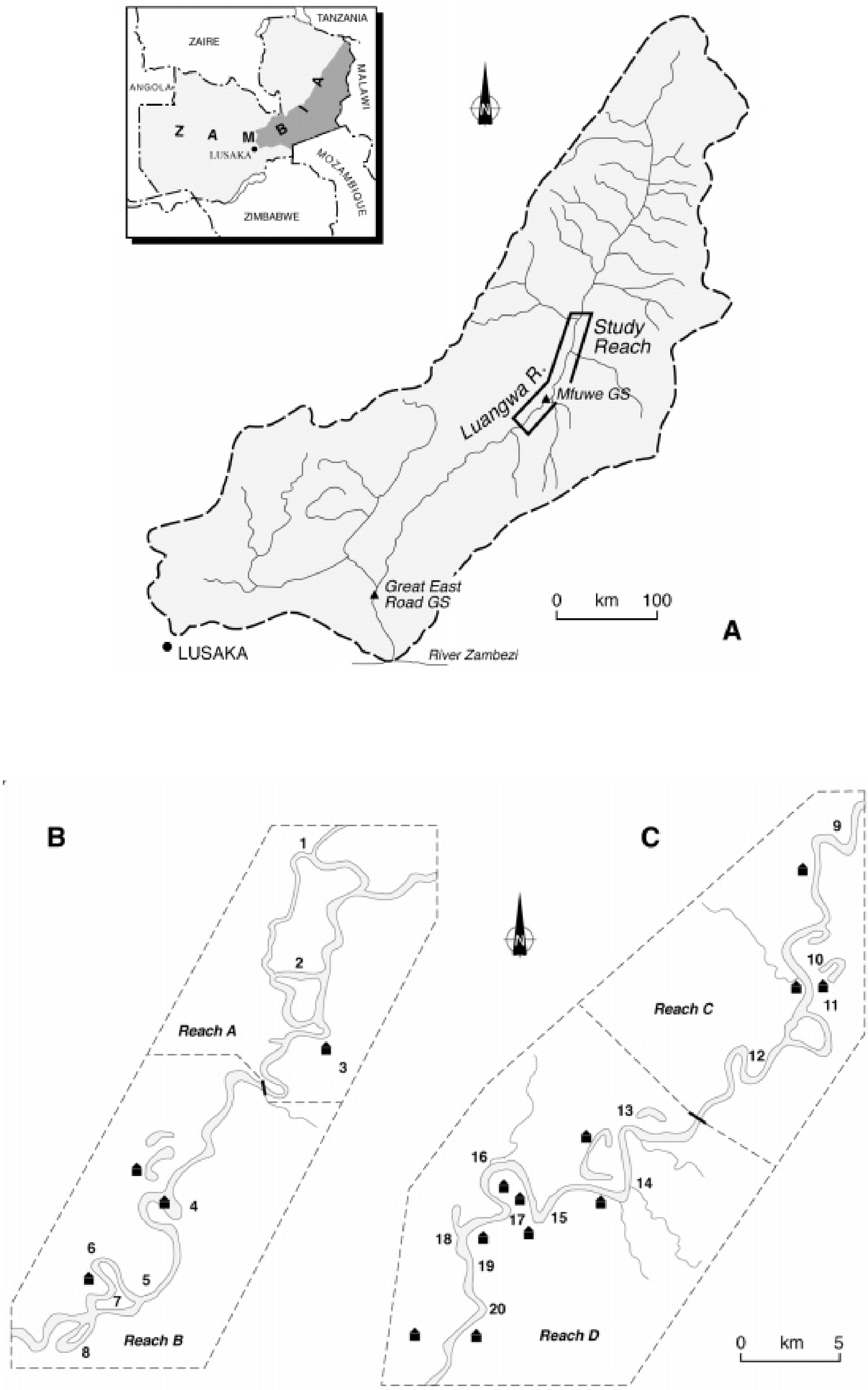

Figure 1. The Luangwa River (A) and studied reaches (B and C); numbers relate to individual meanders described in the text or shown on the following diagrams.

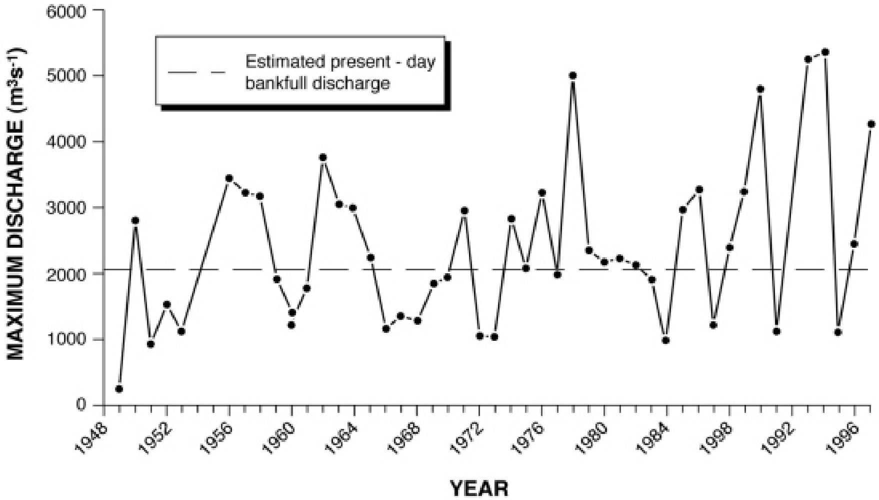

Figure 2. A time series of annual maximum floods on the Luangwa River

Rates of bank erosion from a range of temperate river types have been quoted (<0·1 to 4·5 m a^{-1} being typical; Knighton, 1998) but rarely have they been quantified for tropical meandering rivers. Rutherford and Bishop (1996), using sequential aerial photography, measured average bank erosion rates of 1 to 2 m a^{-1} on actively meandering reaches of the Mekong River, with extension and translation of bends being dominant. Island formation was shown to be more important in terms of inducing rapid bank erosion (<20 m a^{-1}). On the Yom floodplain, also in Thailand, meander bend geometry and position appeared from the sedimentary record to have remained fixed over the last 450 years (Bishop, 1987). In contrast, Salo *et al.* (1986) used multi-date Landsat MSS images of the meandering and anastomosing stretches of the Ucayili and Amazon, and quantified lateral migration rates of 200 m per year between 1979 and 1983.

THE STUDY AREA

The Luangwa River rises in the northeastern part of Zambia close to the Malawi border and flows southwest to join the Zambezi River at the Mozambique–Zimbabwe–Zambia border (Figure 1A). For most of its length the river forms a sand-bed meandering river with a large alluvial plain. Some river sections resemble anastomosing or wandering morphologies in that two or more actively flowing channels are separated for a number of kilometres by large expanses of vegetated floodplain and/or mid-channel bars are present under low and medium flows.

The study reach for the purposes of this paper is from the junction of the Luangwa River with the Mupamadzi tributary in the north to the site of Kafunta safari camp on the shores of the river some 80 km to the south. At Mfuwe within the study area, the catchment area is 73 433 km^2 and the mean annual discharge is 128 m^3 s^{-1} with peaks flow in excess of 2000 m^3 s^{-1}. Located 280 km downstream of Mfuwe is the Great East Road Bridge station with a catchment area of 140 922 km^2 and a mean annual discharge of 626 m^3 s^{-1}.

Analysis of the flow record at Great East Road Bridge shows a modest increase in magnitude of flood peaks over the last 50 years and particularly since 1989 (Figure 2). A regression analysis of annual peak flow against time is significant ($p < 0{\cdot}05$). This is consistent with trends in rainfall and flow elsewhere in eastern Zambia (Sichingabula, 1998).

Within the study area the floodplain is typically 2 km wide with the river channel varying between 100 and 200 m in width; ridge and swale, old infilled channels and cutoff lagoons are all apparent on the floodplain. Typically, eroding river banks are 5–6 m high and composed of sand and silt with fining-upward sequences. Only occasionally and downstream of the study area is the river constrained by gorge-like sections.

The Luangwa valley is underlain by Precambrian igneous and metamorphic rocks as well as by Karoo sedimentary rocks. Soil types found are yellowish-brown sandy soils and dark reddish-brown clays and coarse alluvial sandy soils topped by dark loamy alluvium.

A sizeable part of the Luangwa valley adjacent to the river forms the South and North Luangwa National Parks and has been little impacted by humans. The river itself is unregulated and nowhere does bank protection occur. For the most part the floodplain is also unaffected by land use activities given the National Park status. Indeed it is the diversity of natural geomorphic features and habitats on the floodplain that makes the area one of the best wildlife areas in Africa. Floodplain vegetation consists of a sparse cover of herbs and grasses on sand bars, riparian woodland along the main channel and grassland and Miombo woodland elsewhere.

METHODOLOGY

Field investigations

Visits to the Luangwa River were undertaken in 1990, 1996 and 1997. During the 1997 visit a low-level reconnaissance flight over reaches A–C (Figure 1B and C) was undertaken allowing major planform changes

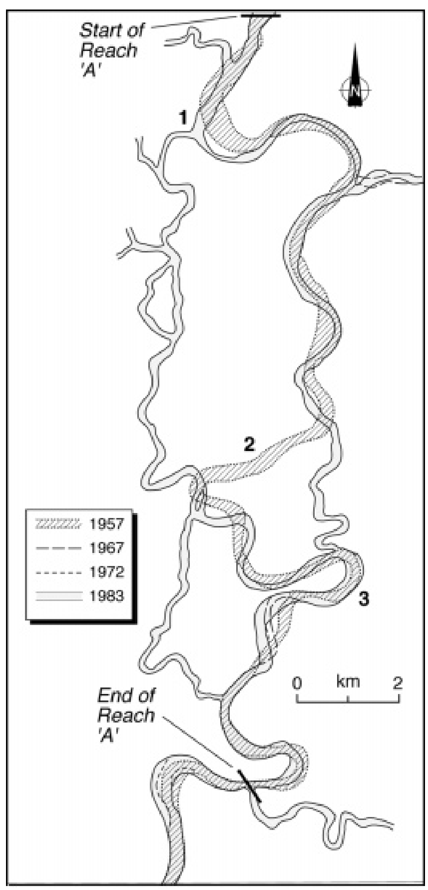

Figure 3. Anabranching in Reach A on the Luangwa River showing the avulsion that occurred between 1967 and 1983. Numbers refer to locations shown in Figure 1B

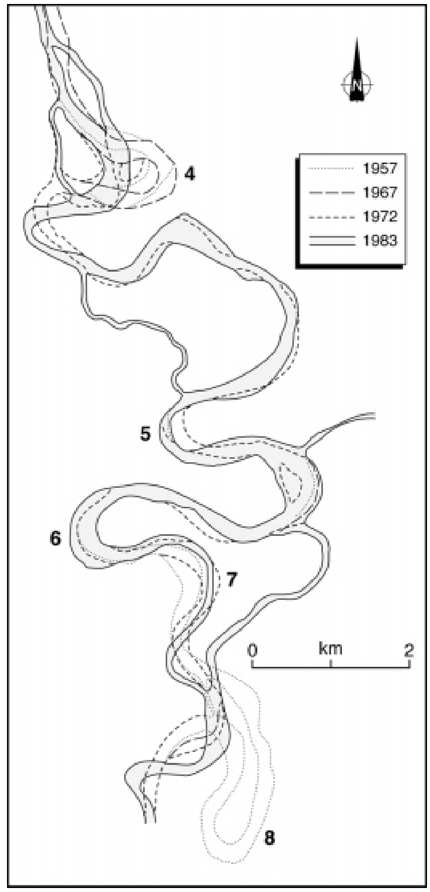

Figure 4. Channel morphology and changes between 1957 and 1983 in Reach B. Numbers refer to locations shown in Figure 1B

(e.g. avulsions and cutoffs) that had taken place since 1988 (the last date from which channel planform was mapped due to aerial photograph availability) to be detected. During the first visit the nature of bank erosion was observed and a baseline survey of the river bank position undertaken on one bend (bend 15; Figure 1C) with fixed points identified. Bend 15 was selected for detailed analysis because of easy access and the fact that access roads to Chinzombo safari lodge and a nearby camping ground had been lost to the river. During the 1996 visit, for the purpose of this study, a repeat survey was undertaken of bend 15, and bank profiling and bank sediment sampling were undertaken at bend 15 and at over 20 other meander bends locations. Following this study and floods during the wet season of 1998–99, Chinzombo safari lodge is being relocated owing to much of it being lost to the river (P. Berry, personal communication).

Aerial photography

Channel planform and floodplain morphology were examined using available aerial photographs (1:20 000 to 1:40 000 scale). Photography was available for years 1956, 1957, 1967, 1972, 1982, 1983 and 1988; only the 1967, 1983 and 1988 photography covered the entire study area. Small format, oblique aerial photographs taken in 1997 were also available for the northern reaches for comparison. Following preliminary analysis of the aerial photographs of the Luangwa, four reaches (A–D) were defined to facilitate further analysis. Reaches were defined according to morphology and the type and level of channel planform instability

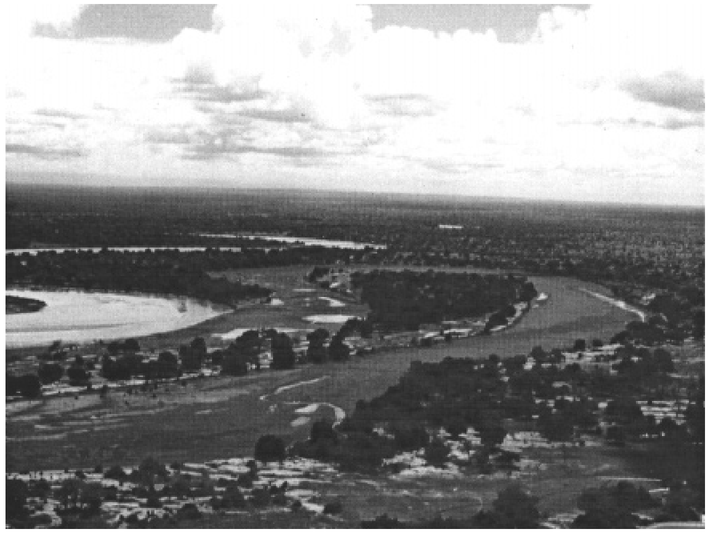

Figure 5. An oblique aerial photograph of bend 8 showing the present-day active channel and the infilled and terrestrialized course of the former river (active in 1956)

exhibited (Figure 1B). Within reaches, the location of specific morphological features and areas of change described in the text are numbered (Figures 1B). For six meander bends (15–20) in reach D, manual co-registration of available aerial photographs was undertaken using a stereo facet plotter; resulting channel outlines were then digitized into a Laserscan GIS where the overlay facility was used to examine rates of bank erosion. Computerized georectification was not undertaken for this study owing to the apparent absence of enough obvious identifiable ground control points or detailed maps of the study area. Comparison of the few known actual distances between fixed points with those obtained from the aerial photographs showed error values of between 3·0 and 9·4 m with average values of 5·9. The smaller scale 1:40 000 photography had the largest error values. These errors need to be taken into account when using the data for analytical purposes. Gurnell *et al.* (1994) found errors of similar magnitude in a comparable study with the conclusion that differences in channel boundary positions in excess of 5 m are likely to be the result of true planform change rather than errors introduced by data handling. Strictly, bank erosion distances less than the maximum error should be ignored (equivalent to 1·8 m a^{-1}). Erosion rates of an order of magnitude larger than the maximum error were observed in the field.

RIVER CHANNEL MORPHOLOGY AND PLANFORM CHANGE

Channel and floodplain morphology (1988–1997)

Reach A. The morphology of the river and floodplain of this reach is generally characterized by low gradients (<0·0001) and a type of anastomosing. Anastomosing is here defined as a river that is divided into totally separate anabranches over distances greater than one meander wavelength. It is synonymous with braiding except that in this case the anabranches are not located in the same channel; further detail on types of anabranching and anastomosing can be found in Knighton (1998). Two distinct anabranches exist. The western one is currently dominant and exhibits a meandering planform along its 14·7 km length (Figure 3). Adjacent to this western anabranch infilled meander cutoffs are apparent. The more easterly anabranch is much smaller and flows over the floodplain devoid of features demonstrating migration by the Luangwa

Figure 6. Photograph showing a concave bank bench at bend 9 taken from Nsefu safari camp. The safari lodge bar can be seen on the right and the concave bank bench to the middle left of the picture below the original outer bank

River except at its northern end. Here the start of the anabranch follows the line of a former meander of the Luangwa River prior to cutoff at some time in the past (pre-1956) and forms a big loop. To the south the anabranch has occupied the line of the much smaller Chibembe tributary. Between the two anabranches 2 km upstream of their merging, a shoaled abandoned channel is also apparent (location 2, Figure 3).

Reach B. Reach B is characterized by a single-thread meandering channel. To the north of the reach it currently exhibits a low sinuosity meandering river but tortuous asymmetric meanders are apparent in the south. In this lower section the floodplain is a series of old infilled meanders and cutoff lagoons of recent origin which show that the river in the recent past was highly tortuous in planform (Figures 4 and 5).

Reach C. Reach C is typically characterized by a medium sinuosity planform with alternating straight reaches and high sinuosity bends such as the one at bend 9 on which Nsefu safari camp is located. On the outside of some of these bends, most notably at Nsefu safari camp, concave bank benches are apparent (Figure 6). Much of the floodplain is characterized by ridge and swale (scroll bars) indicative of channel migration but no old infilled meanders. Only at locations 10 and 11 are classic meanders and old meander cutoffs apparent.

Reach D. Reach D is similar to reach C in that to the north the reach is characterized by a medium sinuosity planform with alternating straight reaches and approximately right-angle bends. These right-angle bends are cutting into older deposits as opposed to recently deposited alluvium. Concave bank benches are present on the outside of many of these tight bends. Here the floodplain contains both cutoff lagoons and extensive areas of scrolls. Downstream there are examples of tight and enlarged meanders and below this a low sinuosity channel but with infilled cutoffs on either side, demonstrating that the channel was once more sinuous; indeed these current cutoffs were active in 1956. Change along this reach is discussed below (bends 15–20).

Planform change (1956–1997)

Types of channel planform instability. The Luangwa River in the last 50 years has exhibited different types of channel change as described below.

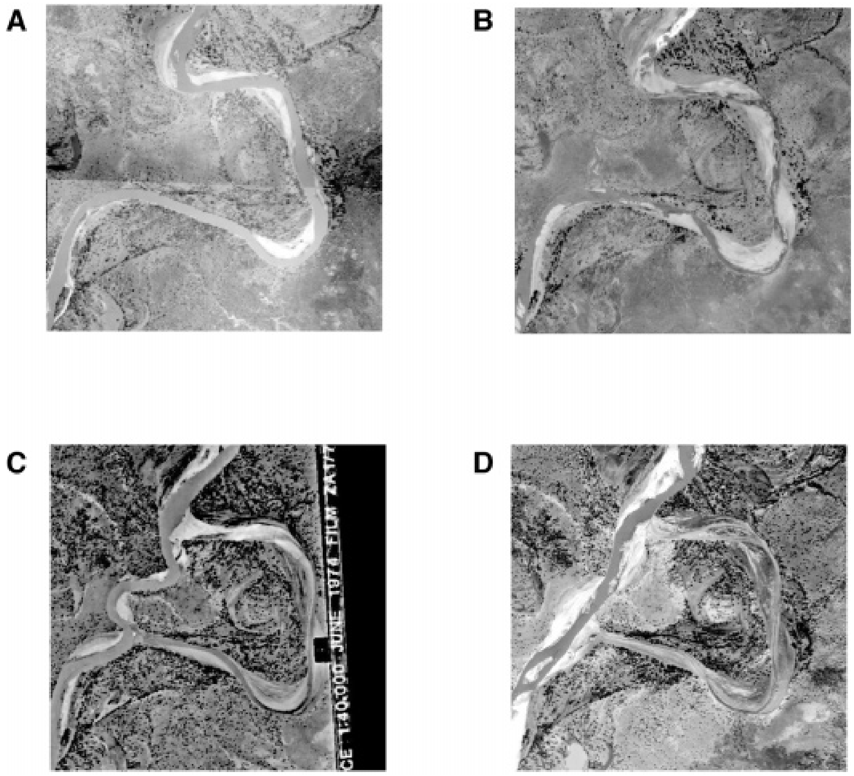

Figure 7. Channel change in the vicinity of the bend 11. (A) In 1956 double-heading is visible on bend 11 and a small tributary course across the neck of the meander is faintly visible. (B) In 1967 the well developed double-headed bend morphology is observed. (C) In 1974 the line of the avulsion can be seen; its course follows that of the tributary course visible in A and B. (D) The 1988 aerial photograph shows infilling and terrestrialization of the cutoff bend, realignment of the avulsion course and lateral point bar formation and early stages of meander development

I. *Avulsions*. Avulsions were observed to occur generally at bends, forming as a result of water superelevation on the outside of banks during flood conditions, and these areas are the first point of overspilling onto the floodplain (P. Berry, personal communication). There is a tendency for avulsions to exploit minor channels, or old courses of the Luangwa River, which enter the main river immediately upstream or downstream of a meander apex where floodplain elevation is lower. The reason for the existence of minor channels near the bend apex is not known. An example of an avulsion which exploited a minor channel is the cutoff at the Luangwa–Kauluzi River junction (bend 11, Figure 7). This most likely occurred in 1971 when one of the highest floods was experienced in the area; in 1967 flow was still around the meander yet by 1974 flow was principally through the avulsion. Another avulsion occurred in the early 1980s when the Luangwa River changed from being single thread to having two main channels, the newly formed 16 km channel for much of its course reoccupying a ‘relic course’ of the river (reach A, Figure 3). The consequence of avulsion and meander cutoff is channel straightening. This is well demonstrated in reach D (bends 18–20), where in 1956 three meanders with a planform indicative of lobing were present but by 1967 had been replaced by a fairly straight channel with large alternating bars. In 1956 signs of overbank floodwaters spilling across one meander are visible but the exact time of avulsion is not known. Three distinct former meander bends, partially infilled and subject to compete drying up in summer, are now present on the floodplain (Figure 8). Meander cutoff by avulsion rather than the gooseneck being eroded completely by bank erosion appears to be the norm given the morphology of palaeomeanders. The large number of palaeofeatures visible in the field and on the aerial

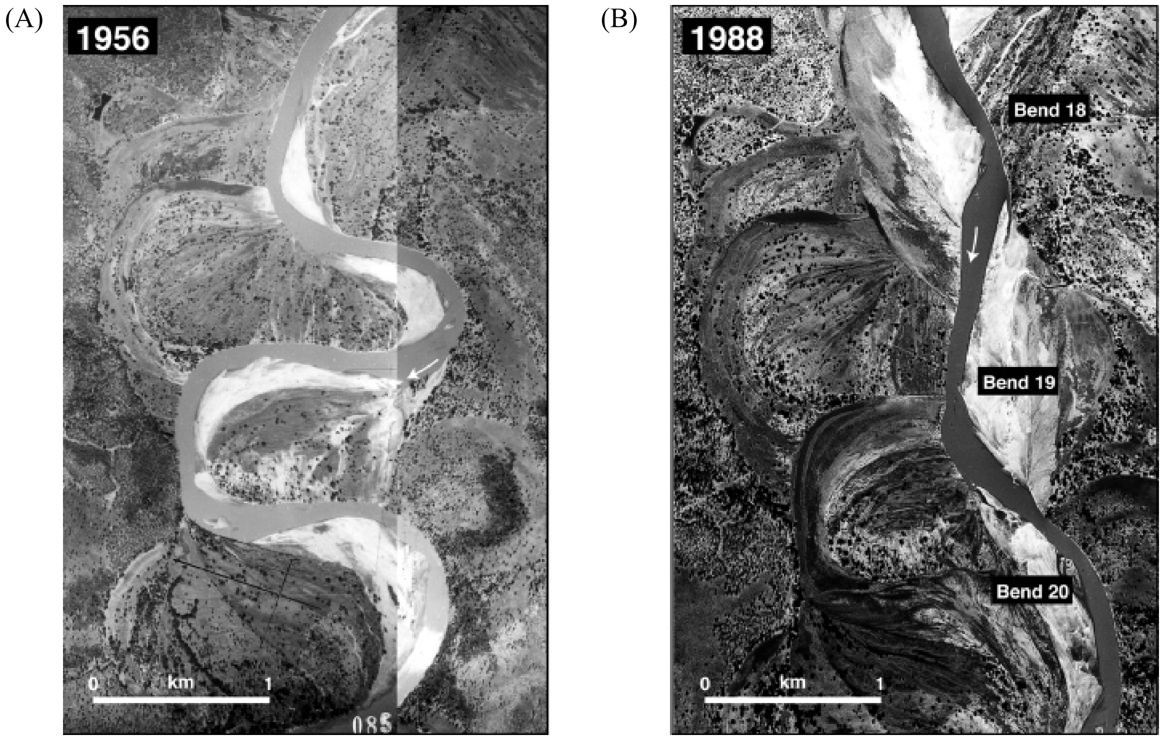

Figure 8. Channel change in the vicinity of bends 18–20 showing avulsion across double-headed meanders: (A) 1956; (B) 1988

photography is indicative of how frequently avulsions have taken place in the past; at least seven have occurred in the last 40 years. The presence of high bank erosion rates and the large number of palaeomeanders combined with low floodplain elevation provide frequent opportunities for the active channel to abutt old courses, or tributary courses that can be reoccupied during large floods.

II. *Anabranching*. The most recent development of anabraching on the Luangwa River occurred in reach A between 1967 and 1983 immediately downstream of the Luangwa–Mupamadzi River confluence (reach A, location 1, Figure 3). In this reach, the Luangwa River flows over a very low gradient ($<0{\cdot}0001$) alluvial plain. It is joined by a number of tributaries that are highly sinuous due to low surface slopes. The anabranched reach was initiated at a minor channel which joined the main river immediately upstream of a meander apex (location 1). Here the Luangwa River breached its banks allowing water to spread over the floodplain scouring the minor channel and making it a permanent westerly anabranch. The eastern anabranch was similarly formed when the main channel was simultaneously shoaled as the water started flowing into the minor channel at the upstream end of a meander bend. This minor channel connected two consecutive bends. The scouring and reactivation of this minor channel in favour of the main channel caused the abandonment of the main channel and its subsequent filling with sand deposits (location 2, Figure 3).

III. *Meander development*. (a) *Outer bank development, rotation and translation*. In many reaches of the Luangwa River following meander loop cutoff and realignment, stages of meander development can be observed on the aerial photographs. Hence at bends 18, 19 and 20 aerial photography captures the form of meander growth since channel straightening (Figure 8). Similarly in reach B increasing sinuosity between 1957 and 1967, then realignment and a new phase of meander growth are captured by the aerial photography (Figure 4). At bend 15 an acute bend had developed by 1956 with the first indications of concave bank development (Figure 9A). Limited development of floodplain vegetation depicted on the aerial photograph also suggests a rapid migration rate and increase in curvature on this bend; lack of tree

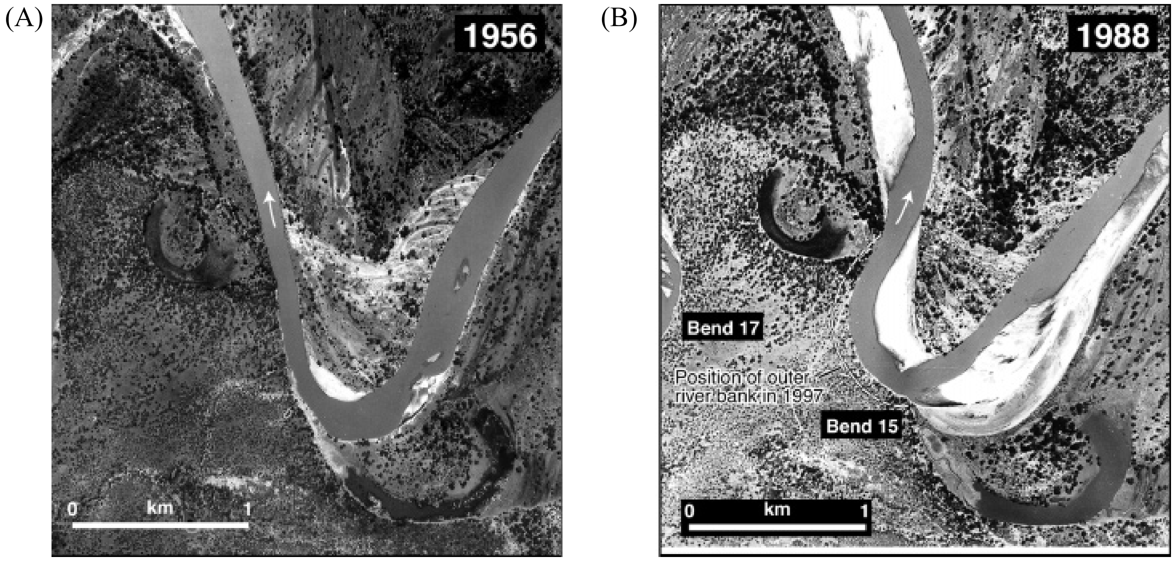

Figure 9. Channel change at bend 15: (A) the nature of the meander in 1956; (B) the meander bend in 1988 with location of the outer bank in 1996 –the concave bench deposit on the outer bank is clearly visible

rings in subtropical climates precludes dendrochronology as a dating method of wooded scroll bars. By 1988 downstream translation and rotation has occurred with early signs of double-heading occurring (Figure 9B). Also visible is a large concave bank bench. Between 1988 and 1996 further erosion occurred, no doubt exacerbated by the large number of high magnitude floods since 1989 resulting in double-heading now being evident (Figure 9B). Approximately 30 m of erosion occurred during the large floods of 1996 and 1998 (P. Berry, personal communication); these values are greater than the average value indicating that with the increasing tendency to high magnitude floods over the last 10 years, bank erosion and instability may have increased. Associated with the concave bench development and double-heading has been a pronounced increase in channel width at all points on the meander development, but particularly upstream of the apex.

(b) *Channel expansion, contraction and meander lobing*. A typical river meander bend concomitantly erodes the outer bank and deposits on the inner bank. The process continues until, according to the model of Hickin and Nanson (1975, 1984), the *r/w* ratio reaches a threshold (normally between 2·0 and 3·0) beyond which meanders tend to become constrained and cease to grow.

For 1956/57, 1967 and 1983, measurements from aerial photographs of *r/w* values for 22 meander bends were undertaken. All values were between 1·4 and 6·5. Between 1956 and 1967 66 per cent of values exhibited an increase. Of those that experienced a decline in *r/w* all had a value of 2·4 to 3·9 at the earlier data. Between 1967 and 1987 as many *r/w* values fell as rose. Lower values in 1987 occurred on meander bends with *r/w* value of between 2·5 and 2·99 in 1967 with the exception of one value (5·18). This anomaly was for the same meander bend that produced the maximum value within the data set (6·5 as recorded in 1957). In other words this meander did not exhibit a reversal to its radius of curvature at a value of between 2·0 and 3·0 in accordance with the findings of Hickin and Nanson (1975, 1984), but became more tortuous and since 1967 has maintained this curvature. However, the bulk of the data suggests that on reaching an *r/w* value of somewhere between 2·4 and 3·9, but more often than not between 2·5 and 3·0, meander contraction and lobing occurs.

At the stage when the meander ceases to grow it may either migrate down-valley, remain stable or reverse the meander development process by contraction. Previous studies suggest that double-heading of meander bends is more common than the reversal process which leads to the formation of concave bank benches (Nanson and Page, 1983; Hickin, 1979). The Luangwa River has an unusually large number of

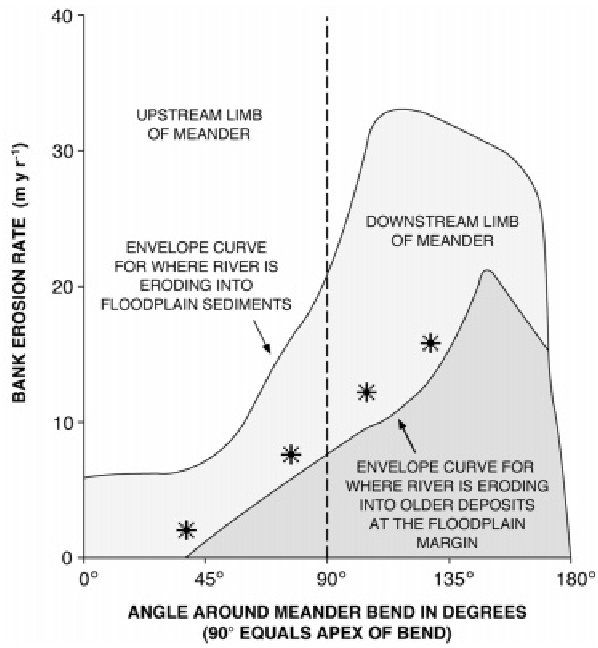

Figure 10. River bank erosion rates in relation to a simple classification of sediments and position on meander bends. Asterix symbols relate to old channel deposits

instances of bend contractions leading to the formation of concave bank benches. Four pronounced concave bank benches within the study reach are apparent (e.g. Figure 6). Bend contraction is reflected in marked differences in bankfull channel width between successive dates; contraction of channel widths by up to 50 per cent was observed, although overall between 1957 and 1988 channel widths increased by 20 per cent.

Rates and mechanisms of bank erosion on meander bends. Comparison of the change in river bank position using GIS overlays on meander bends 15 to 20, as depicted on the 1982 and 1987 aerial photographs, revealed erosion rates of up to 33 m a^{-1} (Figure 10). Rates of bank erosion, however, were highly variable, depending primarily upon position on the bend. For example, at bend 15 analysis of changes in the position of bend 1 between 1982 and 1988 demonstrated a mean annual erosion rate of 8·0 m a^{-1} with values varying between 0 and 21 m a^{-1}, thus indicating a change in meander geometry during the period. Rates of bank erosion also varied with stages of meander development, being greatest during the middle stages of meander evolution and decreasing with increased sinuosity and concave bank bench formation. Comparison of the position of the riverbank in 1988 with that observed in the field, at a number of the bends in 1990, 1996 and 1997, confirmed that these high rates of erosion were representative, or possibly an underestimate, over longer periods. At all six bends maximum erosion rates were beyond the bend apex, as a result of a downstream rotation of bends. Variations in bank erosion rates could also be explained in relation to whether the meander was cutting into recent alluvium or older alluvial sediments at the floodplain margins. Field observations showed that infilled ox-bow lakes and calcareous deposits (possibly representing former hot spring locations; M. Thomas, personal communication) also resisted erosion and the nature of meander development supporting early work of Friedkin (1945) on the Mississippi River. Typically old infilled meanders had between 45 and 75 per cent silt and clay in the lower ($<$25 per cent of bank height), middle (50 per cent of bank height) and upper (75 per cent of bank height) bank profile. In contrast, the rest of the

Table 1. Mean percentage silt clay content in upper, middle and lower river bank sections on the Luangwa River. Numbers in parentheses are number of samples

Morphology type	Upper profile	Middle profile	Lower profile
Infilled meanders	28 (5)	27 (5)	22 (5)
Cemented older deposits	16 (5)	17 (3)	18 (3)
Recent alluvium	32 (10)	18 (9)	14 (6)

floodplain had lower percentages of silt and clay especially in the lower and middle sections of the bank profile (Table I). Bank erosion was seen to result principally from mass failure of riverbank 'blocks' as a result of undermining due to erosion of sand lenses within the lower bank profile (Thorne and Tovey, 1981). Higher up the bank profile finer deposits and the effect of tree roots cause more cohesion and stability. Beam failure and piping have been seen elsewhere to result in high rates of bank erosion and are a feature of banks of composite strength and high sand/silt content.

DISCUSSION AND CONCLUSION

Comparison of planform change with models and previous work

Rates of bank erosion on the Luangwa River appear high in relation to other values quoted in the literature for meandering rivers (Knighton, 1998). Rarely are values above 5 m a^{-1} reported (e.g. Hickin and Sichingabula, 1988); this may relate in part to most studies being undertaken on small rivers and or rivers with cohesive banks. Within the context of sub-tropical African rivers, whether the values found here are exceptional or the norm is not known. Rates of bank erosion appeared to be primarily controlled by meander bend morphology although infilled channels and localized calcium carbonate-rich deposits restricted erosion rates as compared to other recent alluvial facies, as did older alluvial deposits at the floodplain margins. There is some evidence to suggest that although the main mechanisms of bank erosion is scour of basal sand lenses followed by block failure, high magnitude flood events are very important in controlling rates.

Patterns of change appear to substantiate various models of meander development and in particular seem to indicate that critical curvature is important in determining the location of maximum erosion and rate of erosion. Beyond critical curvatures of between 2·5 and 3·5, double-heading and concave bank bench development commonly occur. In particular, the results provide further evidence to support earlier findings (e.g. Woodyer, 1975; Hickin and Nanson, 1984 Figure 5) that on an overwidened meander in fine suspended load rivers, concave bank deposits built up in the upstream end of the pool are a characteristic feature. Avulsions across double-headed meanders were also frequent, with small tributary water courses and old courses of the Luangwa River being exploited.

Assessment of the vulnerability of safari lodges to bank erosion

From the perspective of safari lodge location and vulnerability to erosion, part of the basis for this study, the work to date has shown that on the outside of meander bends safari lodges can be threatened by rapid rates of erosion (>10 m a^{-1}). However, according to the stage of meander bend evolution, buildings located close to the bank on some parts of the bend will have a longer life expectancy than others. Recommendations regarding the siting of safari lodges can take the form of vulnerable and less vulnerable areas. Less vulnerable areas are likely to occur on historically stable straight sections, areas of the floodplain with more cohesive sediments or where the river is adjacent to the valley side, and on the apex of meander bends that have or are undergoing lobing. Particularly vulnerable areas would include: (i) either side of a bend apex on a meander approaching an r/w value of 2·5 because lobing is likely to occur; (ii) the outside of bends that are undergoing expansion (usually $r/w < 3$); and (iii) old channels which are generally more erodible or vulnerable to reoccupation.

Avulsions will always be difficult to predict and will occasionally cut off safari lodges and leave then remote from the active channel. The probability of this occurring can be estimated from the past frequency of occurrence within the study reach and geomorphic indicators of conditions facilitating avulsion. However, predicting if and when it will occur is difficult, particularly with hydroclimatic uncertainty and trends in the flood record.

A GIS-based kinematic model of meander development

As discussed in the introduction, Ferguson (1989) proposed a simple kinematic model which linked river meander development to channel curvature. Hickin and Nanson (1975, 1984), working on the Beatton River, British Columbia, also identified an empirical relationship for meander development whereby migration rates were found to increase with bend tightness up to a critical curvature of $2 < r/w < 3$, and decrease rapidly beyond this value. This can be used to explain secondary lobe development which occurs when migration is locally restricted by excessive curvature. The approach of the Ferguson model and results achieved by Hickin and Nanson have been adopted by the authors as a basis for GIS-based modelling of channel migration on the Lunagwa River. This modelling approach is currently at an early stage but a description of its basis and early results are presented here.

The model approach being developed links the lagged relationship with curvature by representing the river channel as a series of points. Migration at each point i, is perpendicular to the arc i, $i+1$ and occurs at a rate dependent on the curvature of $i-1$ given by the equations:

$$m/w = k(cw/r)^2 \quad \text{for } r > cw$$

$$m/w = k(r/cw)^2 \quad \text{for } r < cw$$

where w is the mean channel width, m is the maximum migration rate, c is the critical curvature, r is radius of curvature and k is a rate constant which will vary between rivers and is dependent on stream power and bank erodiability.

To provide a starting point and initial data for validation of the modelling of channel change, aerial photographs for 1956 and 1967 for study reaches C and D were co-registered. Georectification to a base map was not possible for this area as no accurate map exists with sufficient identifiable features, along the whole length of the river, for use as ground control points. However, the nature of the model, whereby all values are related to channel width, negates the need for actual length values. All measurements were therefore based in units equal to the pixel size of the resampled photographs. Pixels were approximately 6 m in size.

An Arc/Info program was written to apply the model. User input to the model included the channel centre points at one channel width represented as x and y coordinates in an ASCII text file, the values for w, c and k, and the number of iterations (i.e. the number of years simulated). Output was as an Arc/Info coverage showing the predicted new channel centre line as a single arc. The model was then run using the 1956 channel centre line as a starting point, the values of w, c and k as previously determined, and 11 iterations (i.e. years) in an attempt to predict the 1967 channel centre line (Figure 11).

The pattern of meander development is well represented by the model, with lobing and downstream translation of meanders clearly evident and correct prediction a feature of over 50 per cent of the channel length. However, the amount of erosion on some meander bends has been overpredicted while on others it has been underestimated slightly (Figure 11). Nevertheless the modelling approach appears to work well. Discrepancies between actual and predicted erosion are most likely due to inhomogeneity in floodplain sediments and this will be accounted for in further work. Floodplain morphology for the Luangwa River is highly variable and clearly, bank resistance will be highly dependent on the predominant sediments. Differences in bank sediments mean that values of k will vary along the river so although the model predicts well where erosion will occur, it is less accurate on predicting amounts. The next stage of the model will thus be to include values for k that vary with sediment type. Floodplain structures such as abandoned meanders and ridge and swale structures can be delineated from aerial photographs and digitized to provide a

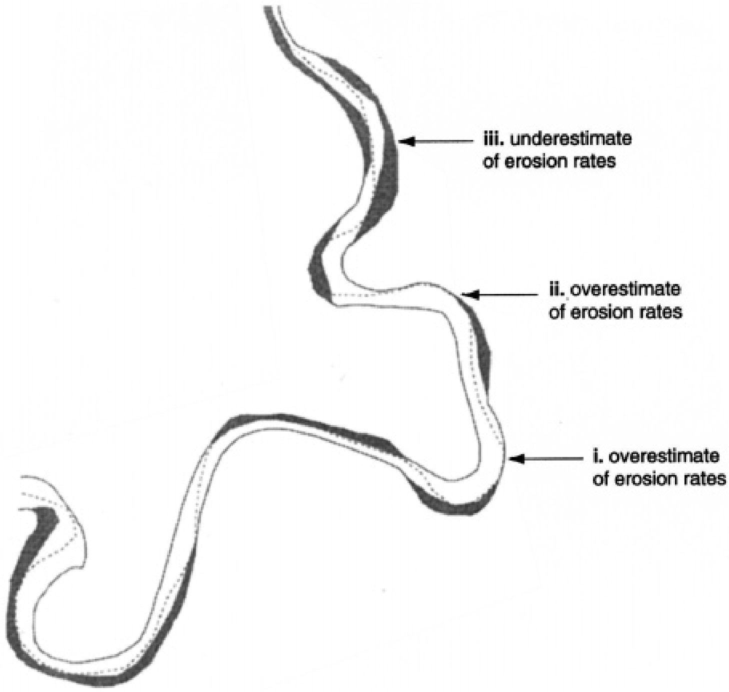

Figure 11. Comparison of observed bank erosion (shaded areas) between 1957 and 1967 for part of reach C (bends 11 and 12) with the output form the modelling indicated by the channel centre line (dashed line)

geomorphological map of the floodplain. The morphological units can then be combined with field data on sediment characteristics for each morphological unit to produce a floodplain bank resistance map which will modify erosion rates as compared to the current model. It is expected that this will greatly improve the accuracy of the predictive model.

Channel response to increasing flood magnitudes and frequency

Figure 2 shows that the last 10 years have experienced a greater frequency of high magnitude events than the preceding 40 years, with four of the largest six floods occurring. This phenomenon may or may not be part of a trend but the response of the channel planform to these events by comparison of up-to-date aerial photography with that in 1983 and 1988 would shed light on the relationship between channel planform change and flood magnitudes. Palaeomeander evidence and the channel dynamics over the last 40 years possibly suggest that the Luangwa River, like so many rivers, is sensitive to environmental change. Based on bankfull channel width measurements on successive aerial photographs, a mean increase in channel width of over 20 per cent has been observed. This may be a response to the trend towards increasing flood magnitudes and presumably sediment loads. This suggests that the Luangwa and other similar rivers are sensitive to changes in hydrological regime in short to medium timescales. Analysis of the morphology of palaeomeanders on the floodplain suggests, although more evidence is needed to confirm the fact, that the Luangwa River was once more sinuous, further highlighting the sensitivity of the channel morphology to hydrological change. Recent increases in flood magnitudes induced by increased precipitation, together with effects of future land-use change, could therefore alter future bank erosion and modes of channel planform change.

ACKNOWLEDGEMENTS

The authors wish to thank the British Council, EDF/Zambian National Parks and Wildlife Service and the University of Zambia for financial support for this research. The cartographic skills of Bill Jamieson and David Aitcheson are also appreciated.

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